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13. ABSTRACT (Maximum 200 words) The field of physical acoustics is a sensitive area in regard to the training of new scientists and engineers, because there are relatively few environments where new techniques in this field are practiced and taught. The Acoustics Program and the Department of Physics at the Pennsylvania State University offer such an environment, and with focused programs in the area of acoustics, sincere and highly motivated graduate students are attracted, and the highest qualified applicants are selected. Thanks to funding from the ONR ASSERT program, additional excellent students have been able to enter the acoustics program. Their projects involved a) the application of modern acoustics techniques to study the physics of fracture and b) the use of resonant ultrasound spectroscopy (RUS) to measure the elastic properties of exotic new materials.				
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TRAINING STUDENTS IN NEW ACOUSTIC TECHNIQUES FOR STUDIES OF FRACTURE AND NONDESTRUCTIVE EVALUATION OF EXOTIC MATERIALS

Description of the project

This final report presents the accomplishments for ONR grant N00014-93-1-0779, "Training Students in New Acoustic Techniques for Studies of Fracture and Nondestructive Evaluation of Exotic Materials". This grant augments the parent ONR grant N00014-92-J-1186, "Innovative Acoustic Techniques for Studying New Materials and New Developments in Solid State Physics". The goal of the program was to involve graduate students in projects which used a) modern acoustics techniques to study the physics of fracture and b) resonant ultrasound spectroscopy (RUS) to measure the elastic properties of exotic new materials.

Description of the approaches

An understanding of brittle fracture, or the catastrophic failure of a brittle material under stress, and the behavior preceding it, is clearly important for industrial and military applications. Although there has been considerable engineering research on fracture, recently theoreticians in condensed matter physics have been applying novel methods in addressing the physics of fracture. In a part of our ASSERT program, we have developed an innovative model experimental system to test some important aspects of the new theories and to establish quantitative connections between the new theories and engineering data. Our model system uses a special open-cell graphite network material which is of considerable interest in itself. Our approach was to circumvent the difficulty of measuring individual atomic bonds breaking in a typical brittle material, and instead measure the breaking of the individual ~ 1 mm size bonds (struts) in the open cell network.

The resonant ultrasound spectroscopy (RUS) technique was developed for the purpose of measuring the elastic constants of new materials, which for one reason or another are available only in small samples, on the order of a few hundred microns in size. For such small samples, measurement with a conventional pulse-echo method would involve great difficulties with transducer bonding, ringing and loading, parallelism of sample faces, beam diffraction, very short pulse generation and detection, and remeasuring to obtain a complete set of elastic constants. Our technique avoided these difficulties by using very thin ($9\text{ }\mu\text{m}$) piezoelectric film for transducers (instead of conventional quartz or lithium niobate) and by measuring a spectrum of acoustic resonances of the sample (instead of the conventional pulse-echo measurement of sound speeds) to determine the elastic constants.

In our measurement technique, the sample, rather than the transducer, resonates, and so acts as its own natural amplifier with a gain equal to the quality factor (Q) of the resonance. The thin transducers are broadband (nonresonant) and for resonant measurement need be only weakly coupled to the sample, so that bonding and loading are not critical. One of the most important features is that all of the independent elastic constants may be determined from a single measurement.

Brief summary of accomplishments

Accomplishments in regard to papers, etc. include one paper published in the prestigious journal *Physical Review Letters* and an invited publication in the magazine *Physics Today*. There were three presentations at workshops and four contributed talks at national meetings of the Acoustical Society of America and the American Physical Society on the RUS research; there were three contributed talks at national meetings of the societies on the fracture research. Both research projects are continuing under the parent grant.

The student involved in the research for most of the period was Philip Spoor, who is currently writing his Ph.D thesis. More recently, Jason White has undertaken the research. Some undergraduates, Steven Savitski, Mike Marotta, and Kurt Fisher, also contributed to the fracture research.

During the period of research, the principal investigator, J. D. Maynard, received the Silver Medal in Physical Acoustics from the Acoustical Society of America.

A list of the papers, etc. is presented in the appendix. Scientific issues and technical aspects of the accomplishments are discussed in the next sections.

Development of a facility for testing new theories for fracture

While studies of fracture have been undertaken for many years, most of the research has involved taking data and developing models for the purpose of predicting a critical size crack which would grow catastrophically under a design load for a given structure. Recently, theorists from condensed matter physics have recognized an analogy between fracture and contemporary physics problems in nonlinear dynamics, directed polymer growth in a random medium, viscous fingering, diffusion limited aggregation, and other problems in self-organized criticality and pattern formation.

Older theories of fracture involved basic energetics (thermodynamics), continuum elastic and rheological equations, atomic level quantum mechanical calculations, and molecular dynamics simulations. The recent theories, in particular the "random bond (or fuse) network", involve statistical physics of random systems. The brittle material is modeled as a network of bonds which are ideally fragile; i.e. they have a linear relation between force and strain up to a threshold force where the bond breaks. The bond strengths are distributed randomly in the network with some probability distribution. Fracture is simulated by applying a stress or strain at the boundaries of the bond network; at some value of the boundary load, one of the internal bonds will break, increasing the load on the remaining bonds, and the process continues until the sample breaks in two. The physical properties which are calculated with such models include the distribution of the stress just prior to breaking, the critical acceleration of a crack at the beginning of fracture, and the scaling of such quantities with the cross sectional area of the system.

In order to test the random bond model, it is necessary to be able to detect individual bond breaking events. In common brittle materials, individual bonds, defects, etc. have

a length scale L on the order of a nanometer or smaller. With a sound speed C on the order of 4000 m/s, the characteristic time scale L/C is less than 10^{-12} s. Experimental measurement of stress pulses with this time scale would be too difficult. To overcome this difficulty, we have developed a model system which embodies the physics of the random bond model, with dynamical effects, but with a greatly increased length and time scale. The material which we use in our model system is a "carbonaceous foam skeleton", or open-cell carbon foam, which consists of a network of graphite struts, about 1 mm in length and 0.2 mm in diameter. These struts play the role of the bonds in the random bond model. Various size samples of the carbon foam are placed under increasing tensile stress, and when a bond breaks, the stress on neighboring bonds changes with a characteristic time scale of 10^{-7} s. By monitoring the system with broadband (100 MHz) transducers, individual bond breaking events are readily detected. Measurements are made with the carbon foam sample and the transducers immersed in water, so that when a bond breaks in the interior of the sample, the signal from the break propagates in the water through the open structure to a transducer just outside the sample. We have tested the validity of this approach, as well as the time resolution of our transducers, by breaking small glass rods behind the sample; very short pulses with sharp (~ 100 ns) leading edges are easily detected.

In order to test the scaling predictions of the random bond models, samples with cross sectional areas covering a range varying by a factor of four have been measured. The facility which we have built for undertaking this research consists of a versatile large scale apparatus, able to produce and sustain up to 2 tons (English) of uniform tensile force for samples ranging from a few centimeters to 25 cm in diameter. The sample to be fractured is centered in a 1 m³ tank of water, and a strain gauge on one of the supporting cables monitors the sample stress. Using several small broadband transducers, detailed signals from the entire fracture process may be recorded. The complete fracture process consists of a train of intermittent precursor bursts, each consisting of one or several individual bond breaking events, followed by the final catastrophe which ruptures the sample into two pieces. The acoustic signals from such a fracture process are captured with the use of two high frequency digital oscilloscopes which can collect a large number of time series in sequence and/or parallel. The fracturing statistics are analyzed to look for dynamical effects, such as paired bond breaking events occurring on the same time scale as the internal reflection of stress waves. The complete set of statistics is related to the applied tensile force, which is recorded for the entire fracture process.

In addition to the statistics of the precursors, etc., the fractal dimension of the rupture surfaces has been measured, using a "slit island" technique. A white plaster cast of the fracture surface is made, painted black, and then partially sanded on a flat surface. The remaining painted region shows the contour at that level. The remaining painted regions at a sequence of levels are imaged with a CCD camera, converted to computer bitmaps, and the perimeter and area of the contours are determined. A log-log plot of area versus perimeter for all of the levels yields the fractal dimension of the fracture surface.

Under the parent grant, larger samples will be measured with more transducers. After

data analysis, papers will be published discussing the method and the results.

Measuring the Isotropy of a Quasicrystal with Resonant Ultrasound Spectroscopy

One of the fascinating properties of quasicrystals is that, unlike conventional crystals, quasicrystals are elastically isotropic. For conventional crystals with high symmetries (e.g. cubic crystals), many physical properties are isotropic, but the property of linear elasticity is fundamentally anisotropic. Thus it is interesting that icosahedral quasicrystals, having long-range order like conventional crystals, must be isotropic in sound propagation. Measuring these properties experimentally has been challenging, because while conventional crystals are fundamentally anisotropic, their elastic constants may be numerically very close to those of an isotropic material, so that it is difficult to distinguish between intrinsically isotropic and anisotropic behavior in a measurement. In our research we used resonant ultrasound spectroscopy to obtain high precision measurements of the elastic constants of both the quasicrystalline and periodic approximant phases of AlCuLi and found, with a significant level of confidence, that the quasicrystalline phase is isotropic (differing from the most nearly isotropic conventional crystal by ten standard deviations), while the periodic approximant is not. This measurement provides an important landmark for the RUS technology, because it represents a measurement for which conventional ultrasonic methods failed; RUS was necessary in order to determine all of the elastic constants self-consistently (without having to remount transducers) and with high precision. Details of this research are presented in the publication listed in the appendix.

In order to obtain the best precision, it was necessary to account for the deviation of the sample from an exactly rectangular parallelepiped. While this could be done with the standard formulation of RUS analysis, it was found that numerical problems appeared. Some problems were solved with subtle program repairs, but others were of a more fundamental nature. Graduate student Phil Spoor reported on these aspects of RUS in an invited talk at the May 1996 meeting of the Acoustical Society of America, and they will form a part of his Ph.D. dissertation, which is now being written.

APPENDIX: PUBLICATIONS, PRESENTATIONS, ETC.

PAPERS PUBLISHED IN REFEREED JOURNALS

P. S. Spoor, J. D. Maynard, and A. R. Kortan, "Elastic isotropy and anisotropy in quasicrystalline and cubic AlCuLi", Phys. Rev. Lett. **75**, 3462-3465 (1995).

PATENTS/APPLICATIONS

Patent Disclosure, "High Speed Digital Imaging System", September, 1995

INVITED PRESENTATION AT WORKSHOPS OR PROFESSIONAL SOCIETY MEETINGS

P. S. Spoor and J. D. Maynard, Workshop on Resonant Ultrasound Spectroscopy, University of Wisconsin, MI, August 1994, "Use of Piezoelectric films and RUS on small samples of novel materials"

P. S. Spoor and J. D. Maynard, Consortium on Resonant Ultrasound Spectroscopy, Santa Fe, NM, August 24-26, 1995. Host: Albert Migliori. "Numerical anomalies in the Rayleigh-Ritz method for calculating the normal mode vibrations of arbitrarily shaped elastic solids".

P. S. Spoor and J. D. Maynard, 131st Meeting of the Acoustical Society of America, Indianapolis, IN, May 13-17, 1996. Host: Albert Migliori, "An investigation of computational problems associated with resonant ultrasound spectroscopy".

CONTRIBUTED PRESENTATIONS AT WORKSHOPS OR PROFESSIONAL SOCIETY MEETINGS

P. S. Spoor, M. J. McKenna, and J. D. Maynard, "A comparison of elastic constants of the quasicrystalline and cubic approximant phases of AlCuLi, using resonant ultrasound spectroscopy", J. Acoust. Soc. Am. **93**, 2276 (1993).

S. R. Savitski and J. D. Maynard, "Observation of Individual Bond Breaking Events in Precursors, Cascades, etc. in the Onset and Progression of Fracture", Bull. Am. Phys. Soc. **39**, 860 (1994)

P. S. Spoor and J. D. Maynard, "Measurements and Analysis of the anisotropy of the AlCuLi quasicrystal and the related R-phase", Bull. Am. Phys. Soc. **39**, 862 (1994)

P. S. Spoor and J. D. Maynard, "Elastic-constant determination of small, near-isotropic crystals using resonant ultrasound spectroscopy: New quasicrystal results", J. Acoust. Soc. Amer. **96**, 3226 (1994)

T. Zhang, S. R. Savitski, and J. D. Maynard, "Observation of individual bond breaking events in the onset and propagation of fracture", J. Acoust. Soc. Amer. **96**, 3227 (1994)

L. C. Krysac, T. Zhang, and J. D. Maynard, "The fracture of brittle carbonaceous form as a candidate for a physical realization of the random fuse model for material breakdown", Bull. Am. Phys. Soc. **40**, 478 (1995)

P. S. Spoor and J. D. Maynard, "Numerical anomalies in the Rayleigh-Ritz method for calculating the normal mode vibrations of arbitrarily shaped elastic solids", J. Acoust. Soc. Am. **97**, 3326 (1995)

HONORS/AWARDS/PRIZES

J. D. Maynard was awarded the Silver Medal in Physical Acoustics by the Acoustical Society of America, November, 1994

Invited publication: J. D. Maynard, "Resonant Ultrasound Spectroscopy", Physics Today **49**, 26-31 (1996).

STUDENTS INVOLVED IN RESEARCH

Graduate Students:

Philip Spoor (Ph.D. candidate, acoustics), Elastic Constants for Aluminum Alloy Quasicrystals and High Tc Superconductors

Jason White (Ph.D. candidate, physics) began summer 1994, Resonant Ultrasound Spectroscopy

Undergraduate students:

Steve Savitski, Senior, 1994 Mike Marotta, Summer, 1995 Kurt Fisher, Senior, 1995-96